



# Control of Next Generation Aircraft & Wind Turbines



Susan Frost, PhD  
Intelligent Systems Division  
NASA Ames Research Center

[susan.a.frost@nasa.gov](mailto:susan.a.frost@nasa.gov)

Subsonic Fixed Wing Project and Subsonic Rotary Wing  
Project, NASA Fundamental Aeronautics Program





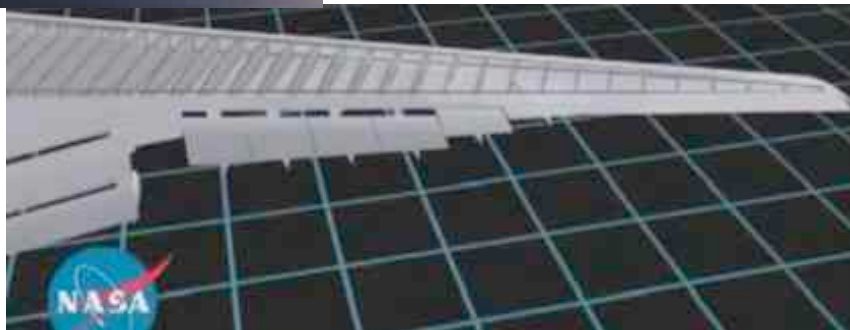
# Some NextGen Control Challenges



↑  
+  
Opportunities



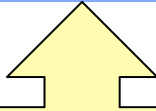
- Many redundant effectors
- Surfaces affecting multiple axes
- Actuator rate & position saturation
- Low control authority
- Lighter structures





# Project Objectives

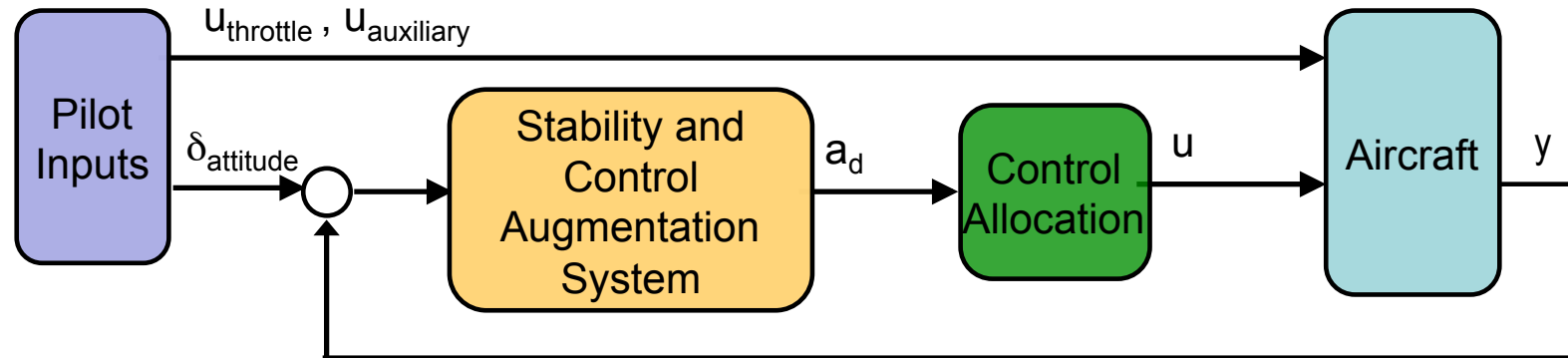
**Task Objective:** Research, develop, and demonstrate a flight control system using real-time structural load feedback to reduce structural loads on the aircraft and remain within its structural limits during normal operation.



This phase of research will not address gust load alleviation, aero-servo elasticity, or flutter suppression (March, 2010)



# Traditional Flight Control System



**Control Allocation:** Find vector of deflections  $u$  such that  $Bu$  matches  $a_d$  under actuator rate and position limits

## Optimal Control Allocation Problem:

Given  $B$ , a desired vector  $u_d$  and  $\varepsilon > 0$ , find  $u$  such that

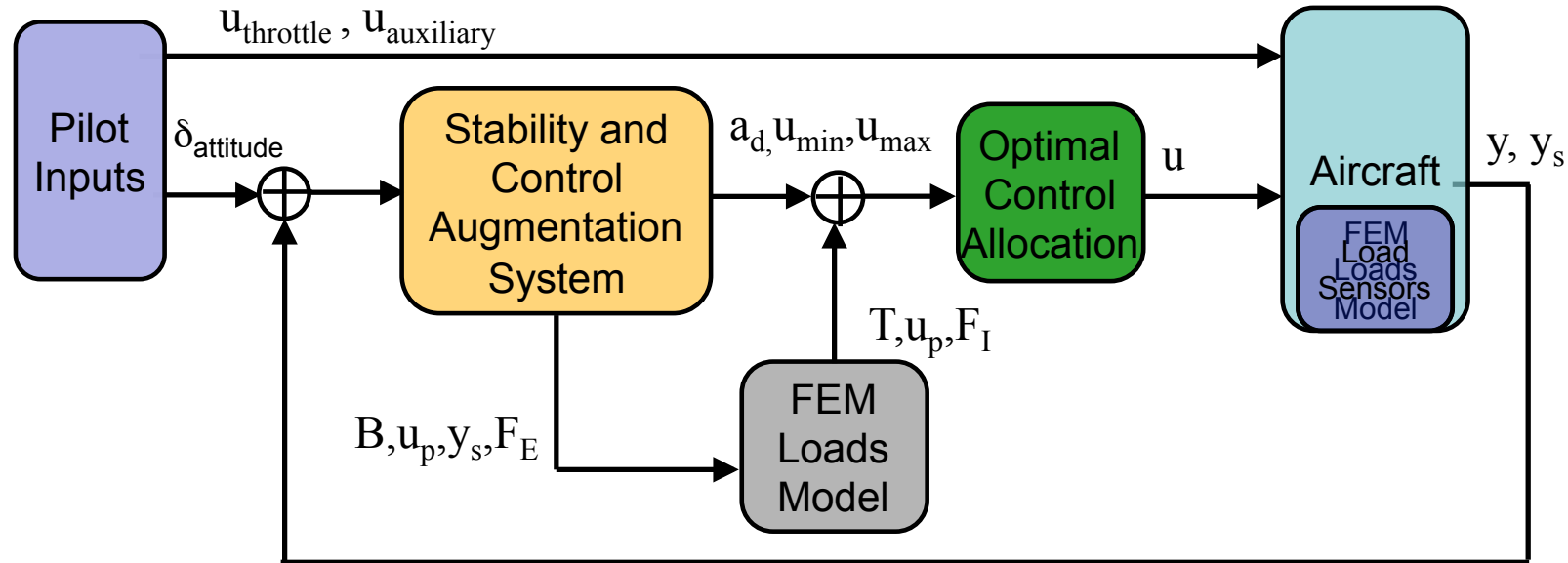
$$J = \underbrace{\|Bu - a_d\|}_{\text{error minimization}} + \underbrace{\varepsilon \|u - u_d\|}_{\text{control minimization}}$$

**No Structural Constraints!!**

is minimized, subject to  $u_{\min} \leq u \leq u_{\max}$ ,  $|\dot{u}| \leq \dot{u}_{\max}$



# Proposed Framework



$u_p$	previous commanded surface positions
$T$	incremental loads matrix, where $T(u-u_p)$ gives the incremental loads at critical points when deflections are given by $u$
$y_s$	real-time structural loads from sensors (or model in sim)
$F_E$	lift and other external moments and forces
$F_I$	augmented real-time structural loads at critical points



# Optimal Control Allocation

## Optimal Control Allocation Problem:

Given  $B$ , a desired vector  $u_d$  and  $\varepsilon > 0$ , find  $u$  such that

$$J = \underbrace{\|Bu - a_d\|_1}_{\text{error minimization}} + \underbrace{\varepsilon \|u - u_d\|_\infty}_{\text{control minimization}}$$

is minimized subject to:

$$u_{\min} \leq u \leq u_{\max}, \quad |\dot{u}| \leq \dot{u}_{\max}, \quad F_I + T(u - u_p) \leq F_{I,\max}$$

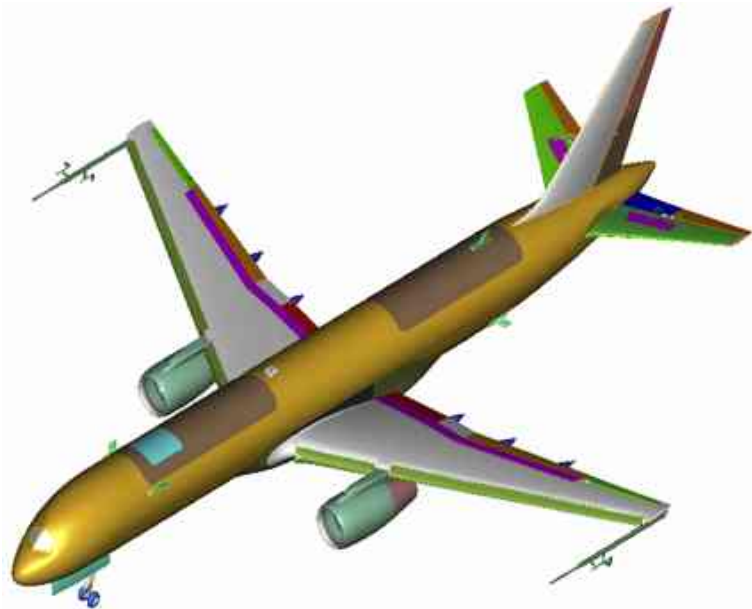
where  $F_{I,\max}$  is the load limits at the critical points

Can also be formulated with loads minimization, with constraints given above:

$$J = \|Bu - a_d\| + \varepsilon \|u - u_d\| + \underbrace{\gamma \|F_{I,\max} - F_I + T(u - u_p)\|}_{\text{load minimization}}$$



# Up-scale GTM Simulation



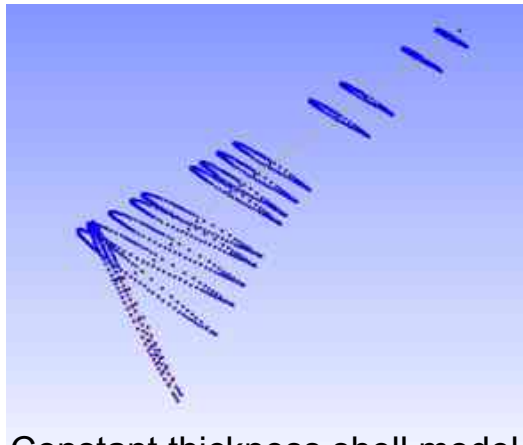
5.5% GTM-T2 Solid Model

## Up-scale GTM Simulation

- Simulink model based on 5.5% dynamically scaled aircraft derived from wind tunnel & flight test data
- Up-scaled by incorporating Reynolds adjusted aero tables
- Actuator models sized for up-scale GTM
- NASA Glenn's CMAPSS (simp2) engine data
- GTM bare airframe
- 6 ailerons, 4 elevons, 2 rudders, 2 stabs, 2 flaps
- Vehicle Management System
  - sensor processing module
  - mission manager
  - guidance/control
- Vehicle Control Augmentation System
  - reference model dynamic inverse controller
  - optimal control allocator

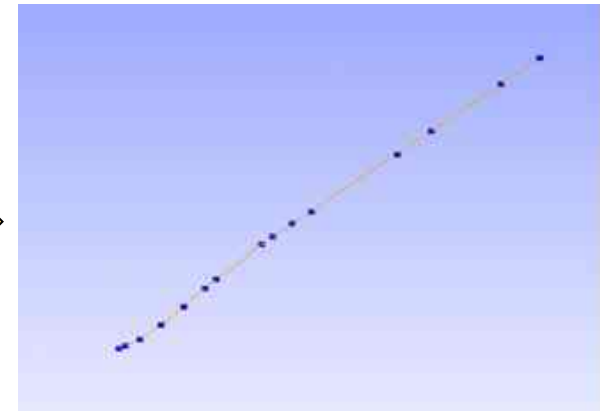


# Structural Modeling Approach



Constant thickness shell model

Model GTM right wing using connected beams



Finite Element Model (FEM)

## Assumptions

- Static conditions (dynamics will be added later)
- Lift is elliptically distributed over wings
- Roll is produced by anti-symmetric forces on ailerons
- Aileron forces are proportional to surface deflections

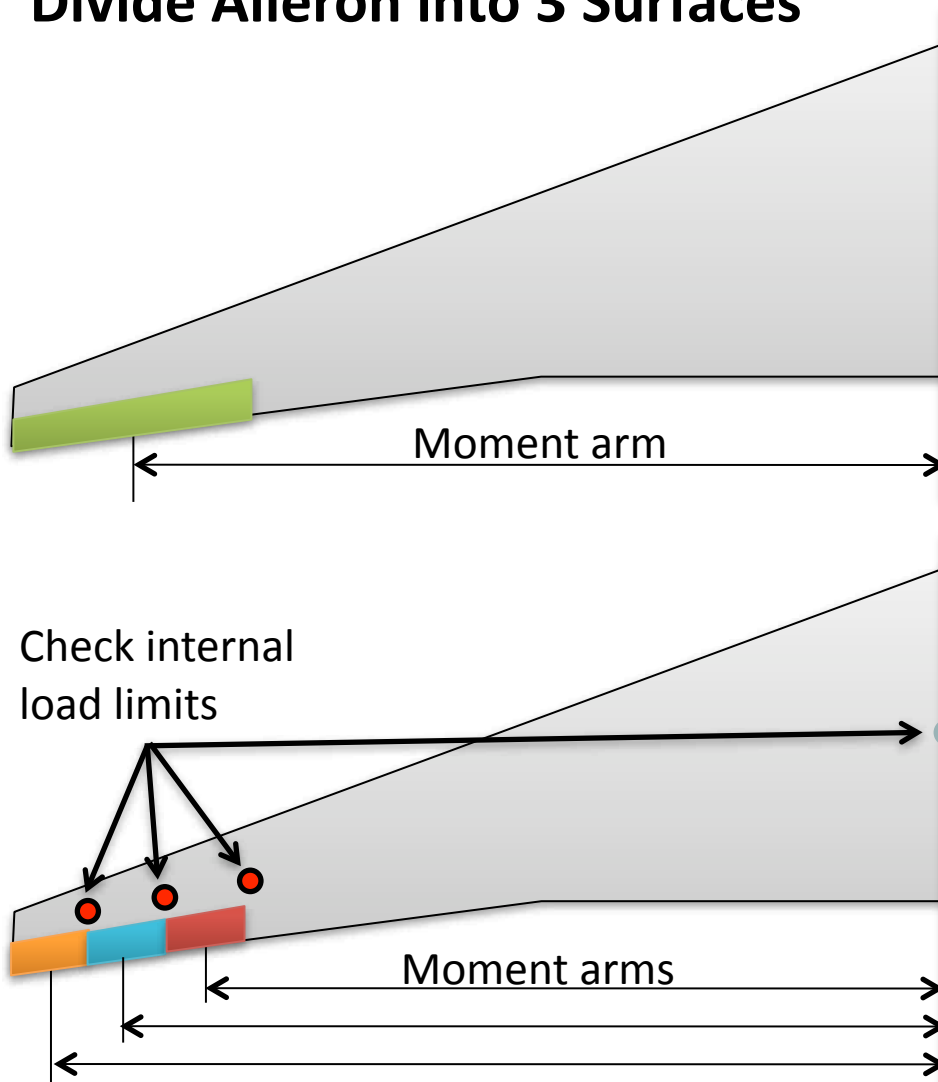
## Finite Element Analysis

- FEM wing model currently has 90 DOFs (more will be added)
- Stiffness matrix  $K$  is derived from FEM
- $K^{-1}$  is computed off-line, enabling real-time calculation of structural loads
- $K^{-1}$  and  $B$  are used to determine  $T$  (incremental load matrix)



# Simulation Test Case

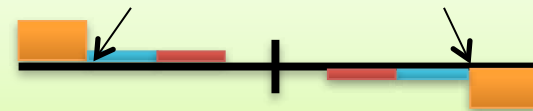
## Divide Aileron into 3 Surfaces



### COMMANDED ROLL MANEUVER

Both produce same roll moment

Structural load limits exceeded



Structural loads within limits



Altitude 30,000 ft  
Mach 0.85



# Outline



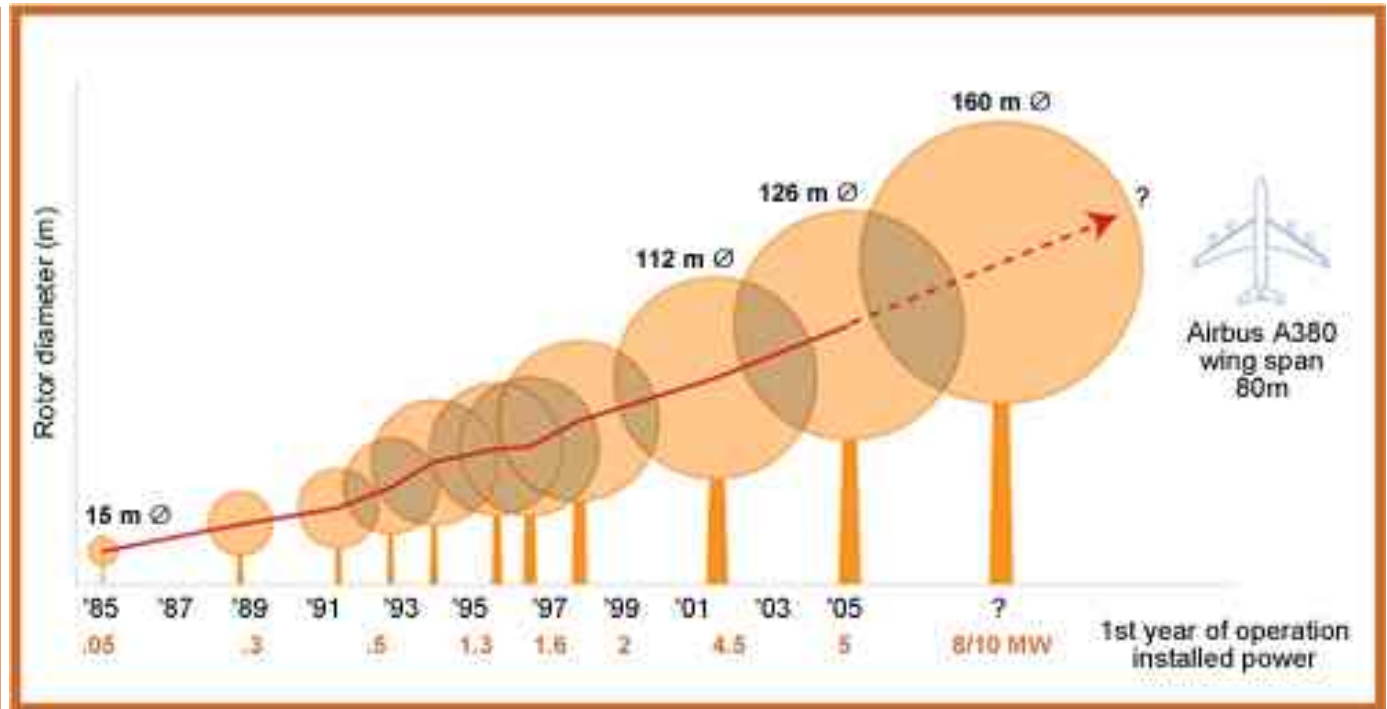
- Wind Energy Quick Overview
- Utility-Scale Turbines
- Wind Turbine Modeling & Control
- Adaptive Pitch Controller
- Simulation
- Residual Mode Filter
- Results



# Evolution of Wind Turbines



Turn of the Century Wind Mill



Source: [www.owenscorning.com](http://www.owenscorning.com)

- Wind speed can increase by 20% with a 10 meter increase in height
- Average annual wind speed of 6.3 mps (14.1 mph) 50 meters above ground needed for economic feasibility
- Largest turbine in production is 126 meter diameter (5 MW)

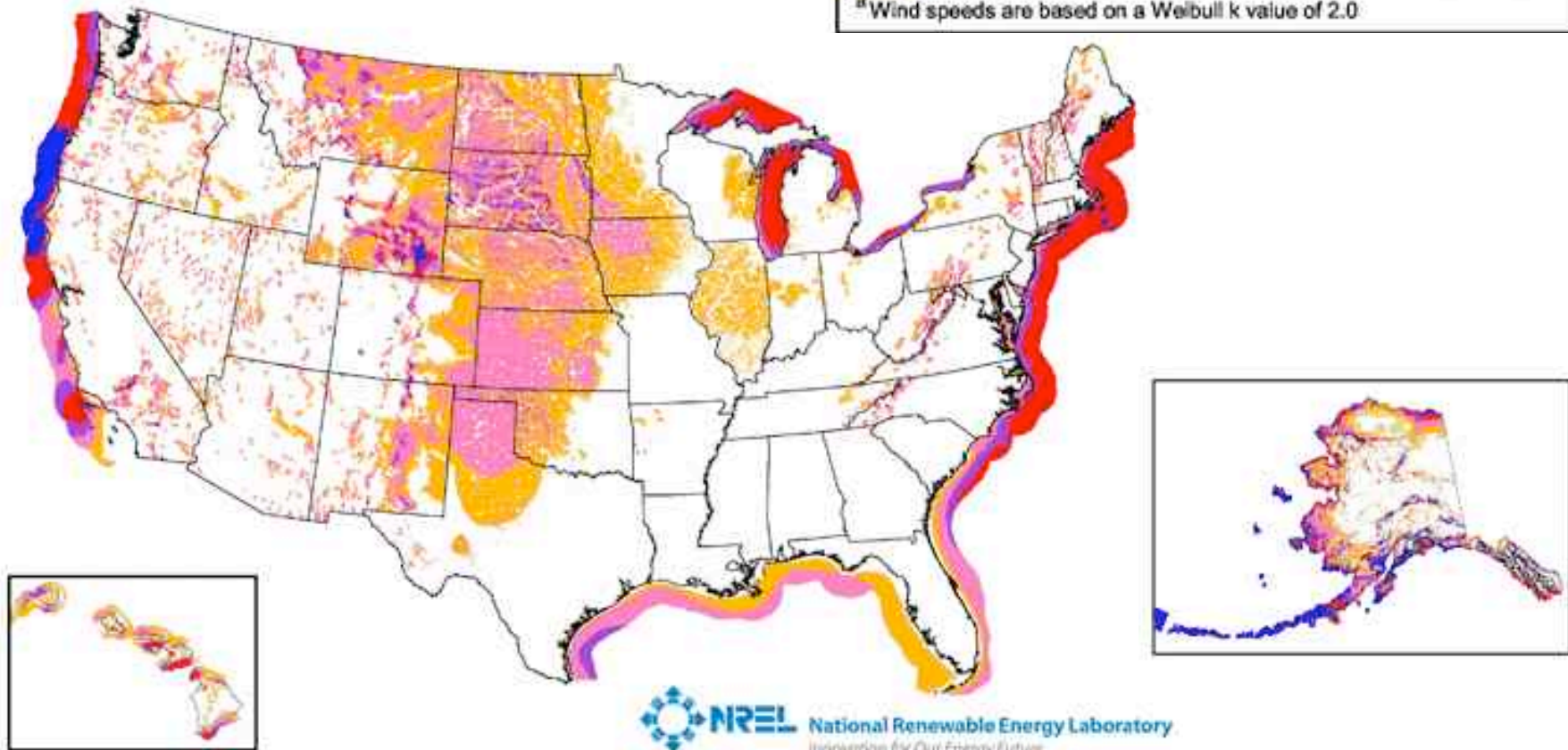


# Wind Power Resources in US

- Class 4 or higher wind suitable for utility-scale turbines
- Class 3 areas could have higher wind power at 80 meters

Wind Power Classification				
Wind Power Class	Resource Potential	Wind Power Density at 50 m $W/m^2$	Wind Speed <sup>a</sup> at 50 m m/s	Wind Speed <sup>a</sup> at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

<sup>a</sup>Wind speeds are based on a Weibull k value of 2.0





# Scary Green Energy Jobs





# Wind Energy Research Areas



- Modeling, Design, Materials
- Control, Optimization, Acoustics
- Sensors, Actuators, Installation
- Component Test, Health Monitoring





# Research Areas of Interest to NASA Ames

- Need improved models for wind turbine & operating environment
- Wind turbine models do not accurately predict performance



NREL Wind Turbine at Ames Wind Tunnel



- Wind turbines still fail and exact cause usually unknown
- Mitigation of loads on drive train, blades, and tower
- Turbine health monitoring
- Enhanced energy capture
- Design & Optimization



# Utility-Scale Horizontal Axis Wind Turbine



Image: NWTC

## Utility-Scale HAWT's

- Rotor Diameter:
  - 40-95 m Onshore
  - 90-114 m Offshore
- Tower: 25-180 meters
- Capacity:
  - 0.1-3 MW Onshore
  - 3-6 MW Offshore
- Start up wind speed: 4-5 mps
- Max operating wind speed ~16 mps
- Low speed shaft: 30-60 RPM
- High speed shaft: 1000-1800 RPM



# Wind Power

## Amount of power produced by a wind turbine:

$$P = \frac{1}{2} \rho A C_p \omega^3$$

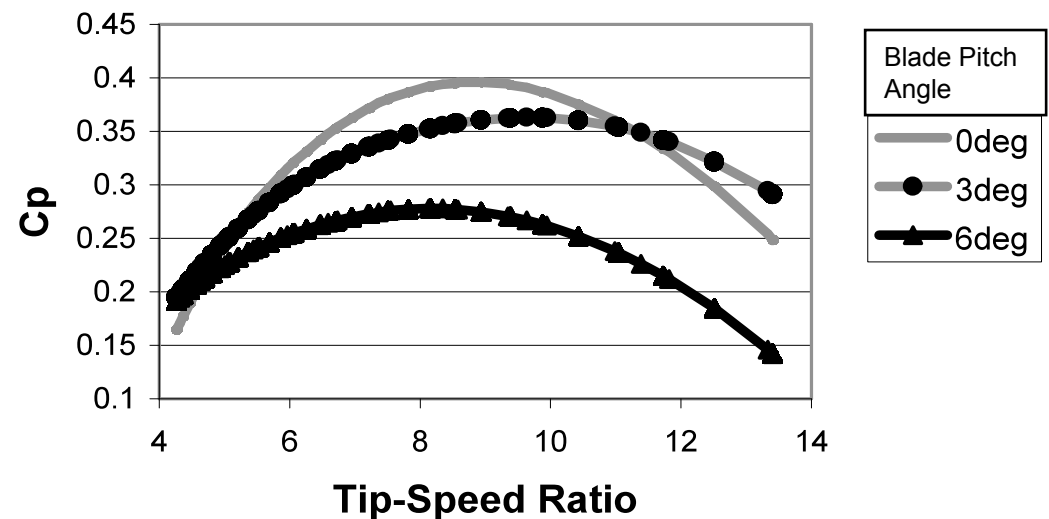
$\rho$   $\equiv$  air density

$A$   $\equiv$  rotor area

$C_p$   $\equiv$  power coefficient

$\omega$   $\equiv$  wind velocity

Plot of Power Coefficient versus Tip-Speed Ratio



$$\lambda = \frac{\omega_T R}{\omega} \equiv \text{tip - speed ratio}$$

$R$   $\equiv$  rotor radius

$\omega_T$   $\equiv$  rotor speed



# Most Basic Governing Equation

$$I_{rot} \dot{\omega}_T = T_{aero} - T_{gen}$$

$$T_{aero} = (1/2) \rho A R C_q (\lambda, \beta) \omega^2$$

$$\text{TSR} : \lambda \equiv R \omega_T / \omega$$

$$\begin{cases} T_{aero} \equiv \text{aerodynamic torque} \\ T_{gen} \equiv \text{generator torque} \\ I_{rot} \equiv \text{rotor inertia} \end{cases}$$

$\omega_T$ =rotor speed       $\omega$ =windspeed

$\rho$ =air density       $A$ =rotor swept area

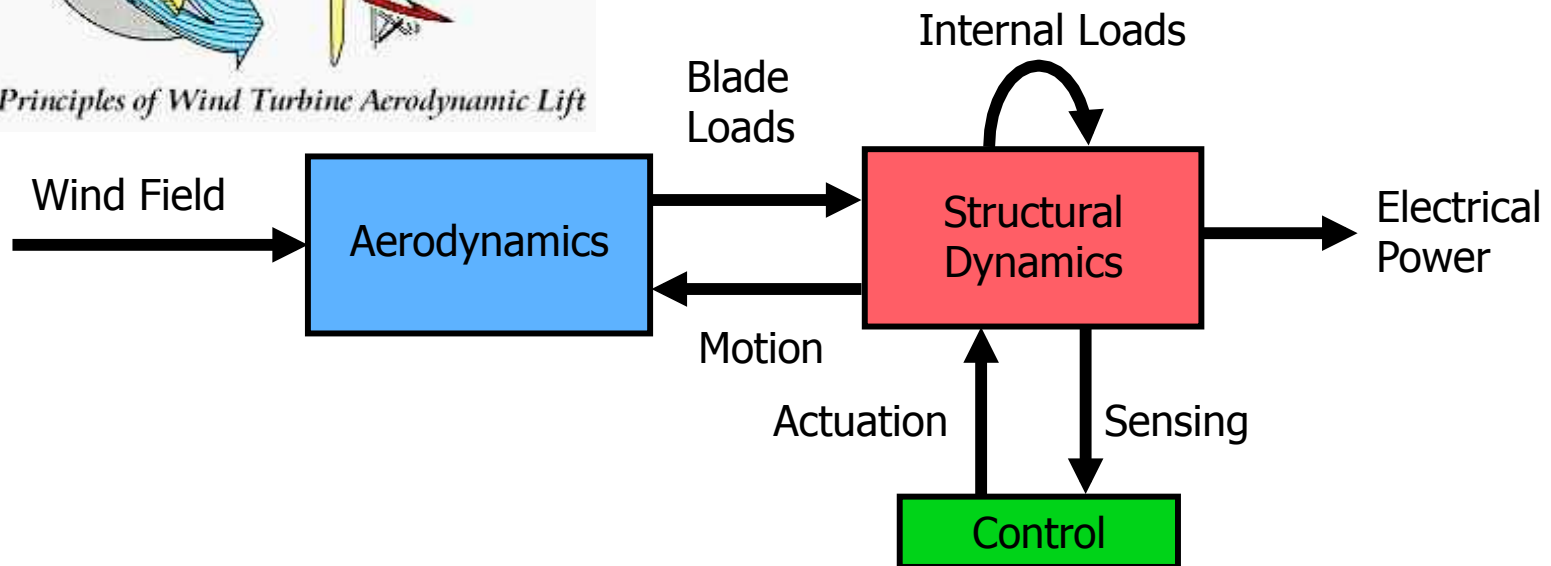
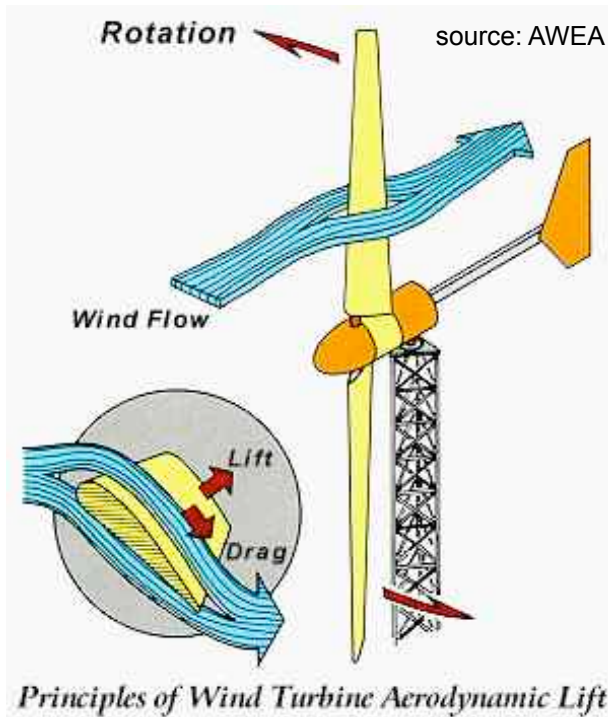
$R$ =rotor radius       $\lambda$ =tip speed ratio

$\beta$ =blade pitch angle

$C_q$ =coefficient of aerodynamic torque



# Dynamic Subsystems

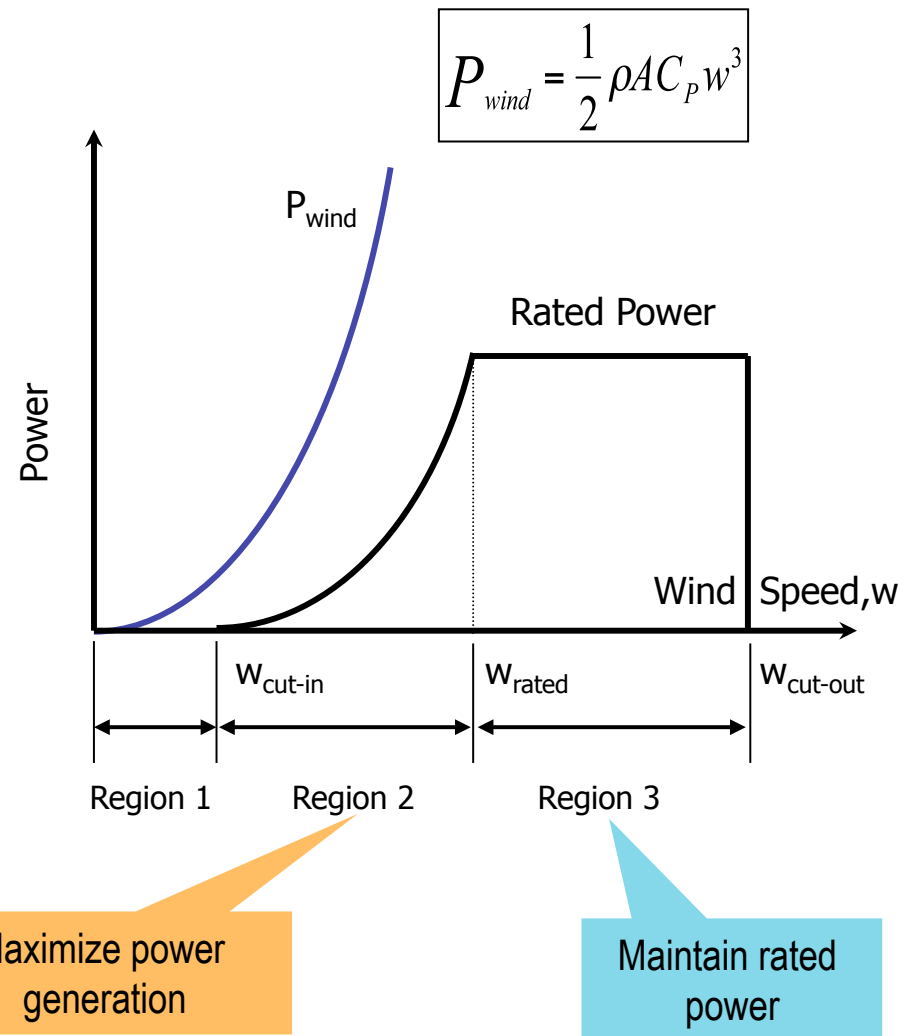




# Operating Regions & Control Strategies

## Control Objectives:

- Reduce cost of wind energy
- Enhanced power capture
- Mitigate loads to decrease fatigue and failure
- Maintain safe turbine operation





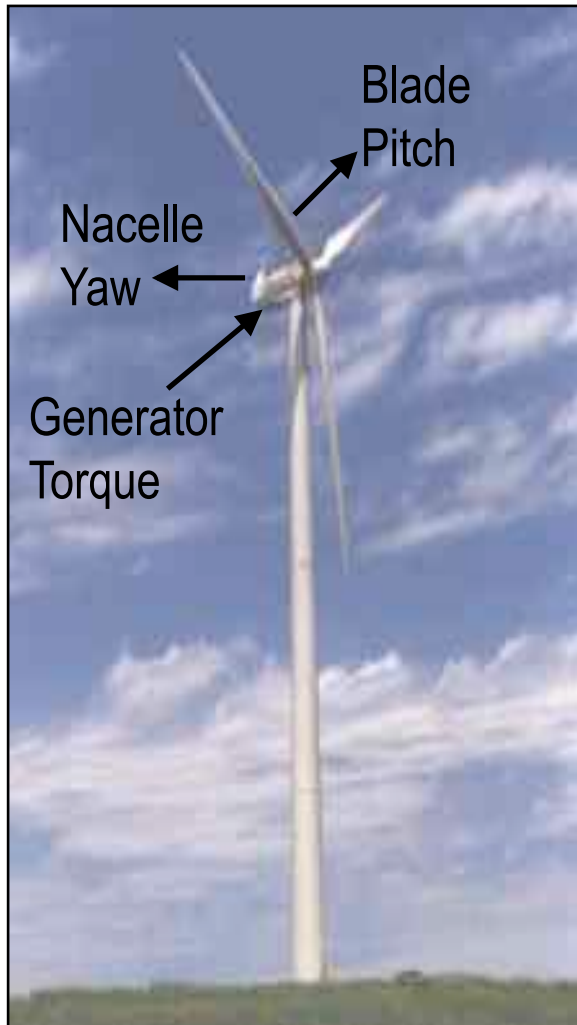
# Pitch-Controlled Wind Turbines

- Region 2:
  - Control generator torque to yield optimum power
  - Hold blade pitch constant
- Region 3:
  - Control blade pitch to maintain constant rotor speed
  - Generator torque held constant





# Wind Turbine Actuation



Control Actions

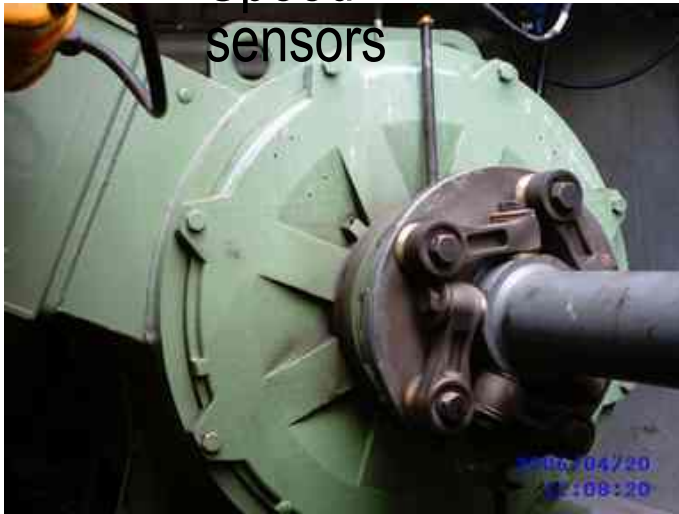


Pitch Actuators



# Sensors for Control and Modeling

- Speed sensors



- Accelerometers



- Anemometers and wind vanes



- Electrical power sensors



- Strain gages





# Wind Turbine Control and Adaptive Control

## Why is control important?

- Future trends in wind turbines
  - Large multimegawatt turbines placed on tall towers or offshore
  - Softer more flexible systems
  - Increased likelihood of destructive structural dynamic loads and responses, excited by highly turbulent flow
- Control can increase efficiency, uptime, and lifespan of turbines

## What is adaptive control?

- Uses plant output to modify control law to respond to unmodeled plant dynamics, uncertain operating environment and time varying parameters

## Benefits of adaptive control

- Good for poorly modeled plants with uncertain operating environments
- Requires less modeling of turbine and its operating conditions
- Reduces controller design time since less tuning is required
- Changes to turbine may require no controller modification



# Direct Adaptive Control with Rejection of Disturbances

- Plant is linear time-invariant (LTI) (\*) 
$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{\Gamma}\mathbf{u}_D \\ \mathbf{y} = \mathbf{C}\mathbf{x}; \mathbf{x}(0) = \mathbf{x}_0 \end{cases}$$

where  $\mathbf{x}$  is plant state,  $\mathbf{u}$  is control input,  $\mathbf{y}$  is sensor output, and  $\mathbf{u}_D$  is disturbance input and plant parameters  $(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{\Gamma})$  are unknown

- Disturbance input comes from a **Disturbance Generator**: 
$$\begin{cases} \mathbf{u}_D = \mathbf{\Theta} \mathbf{z}_D \\ \dot{\mathbf{z}}_D = \mathbf{L} \phi_D; \mathbf{z}_D(0) = \mathbf{z}_0 \end{cases}$$

- Disturbances are of **known** form (i.e.,  $\phi_D$  are basis functions of disturbance), but **unknown** amplitude

- Control objective**: Cause Plant output  $\mathbf{y}$  to asymptotically track 0

- Output error**:  $\mathbf{e}_y \equiv \mathbf{y} - 0 \xrightarrow{t \rightarrow \infty} 0$

- Adaptive control Law**: 
$$\mathbf{u} = \mathbf{G}_e \mathbf{e}_y + \mathbf{G}_D \phi_D$$

- Adaptive gains**:  $\dot{\mathbf{G}}_e = -\mathbf{e}_y \mathbf{e}_y^T h_{11}, \dot{\mathbf{G}}_D = -\mathbf{e}_y \phi_D^T h_{22}, \text{ with } h_{11}, h_{22} > 0$

For Closed-Loop Stability Analysis, see: Frost, Balas, Wright, IJRNC (2009)



## Closed-Loop Stability Result

Theorem: Suppose the following are true:

1. All  $\mathbf{u}_m$  are bounded (i.e., all eigenvalues of  $\mathbf{F}_m$  are in the closed left-half plane and any eigenvalues on the  $j\omega$ -axis are simple);
2. The reference model,  $(\mathbf{A}_m, \mathbf{B}_m, \mathbf{C}_m)$ , is stable;
3.  $\phi_D$  is bounded (i.e., all eigenvalues of  $\mathbf{F}$  are in the closed left-half plane and any eigenvalues on the  $j\omega$ -axis are simple);
4.  $(\mathbf{A}, \mathbf{B}, \mathbf{C})$  is Almost Strict Positive Real (ASPR) (i.e.  $\mathbf{CB} > 0$  and the open-loop transfer function is minimum phase)

Then the adaptive gains  $\mathbf{G}_u$ ,  $\mathbf{G}_m$ ,  $\mathbf{G}_e$ , and  $\mathbf{G}_D$  are bounded, and asymptotic tracking occurs, i.e.  $\mathbf{e}_y \equiv \mathbf{y} - \mathbf{y}_m = \mathbf{C}\mathbf{e}_* \xrightarrow{t \rightarrow \infty} 0$



## Adaptive Pitch Control in Region 3

- **Objective:** Regulate generator speed in Region 3 and reject step disturbances
- Controller designed with extended DAC approach to collectively pitch blades and hold generator torque constant
- Uniform disturbance of wind gust across rotor can be modeled by a step function of unknown amplitude, so  $\phi_D = 1$

- **Adaptive control law:** 
$$\begin{cases} \mathbf{u} = \mathbf{G}_e \mathbf{e}_y + \mathbf{G}_D \\ \dot{\mathbf{G}}_e = -\mathbf{e}_y \mathbf{e}_y^T h_{11} \\ \dot{\mathbf{G}}_D = -\mathbf{e}_y h_{22} \end{cases}$$

- Adaptive controller gains were tuned to minimize generator speed error while keeping the blade pitch rate in a range similar to baseline PI controller's
- Gains used in the adaptive controller were  $h_{11} = 14.0$  and  $h_{22} = 4.0$



# NREL's NWTC Test Facility



image credit:  
NREL

National Renewable Energy Laboratory's (NREL)  
National Wind Technology Center (NWTC) Test Facility  
Golden, Colorado



# Controls Advanced Research Turbine (CART)



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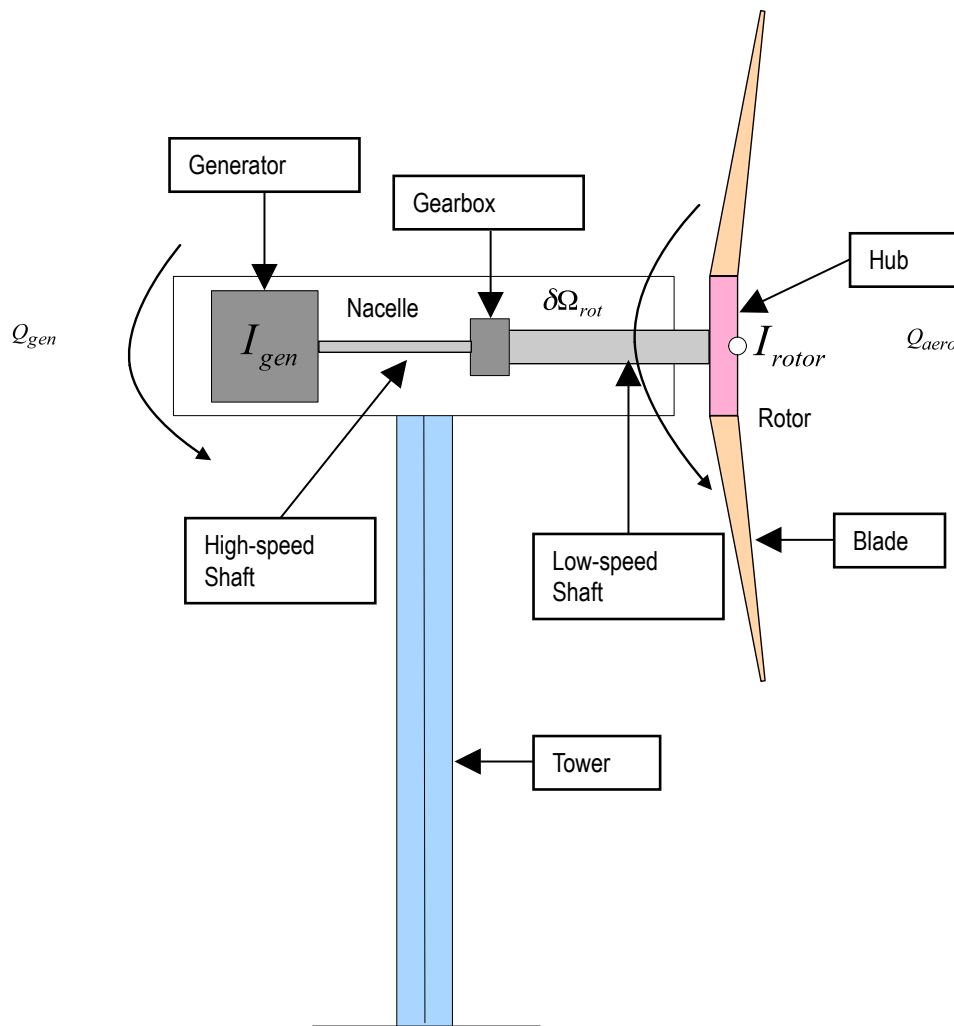


images credit:  
NREL

NWTC, Golden, Colorado



# CART Specifications



## CART Specifications

- Variable-speed, two-bladed, teetered, upwind, active-yaw
- Rotor Diameter: 43.3 m
- Hub Height: 36.6 m
- Rated electrical power: 600 kW at 42 RPM in region 3
- Region 3 Rated generator speed: **1800 RPM**
- Power electronics command constant generator torque
- Blade pitch rate limit:  **$\pm 18$  deg/sec**
- **Baseline PI Pitch Controller**



# FAST Simulator for CART



image credit:  
NREL

**F**atigue

**A**erodynamics

**S**tructures

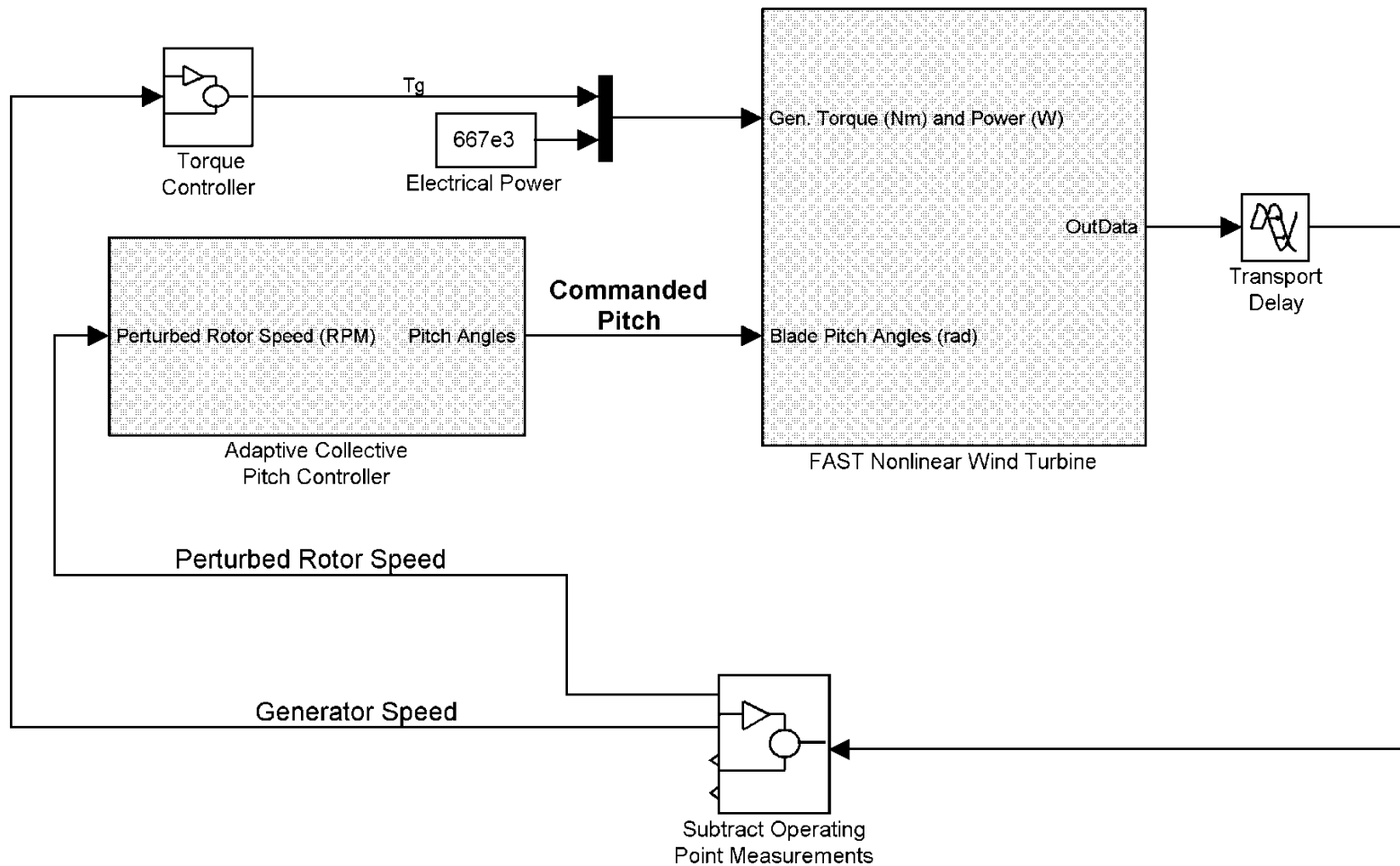
**T**urbulence

- Aeroelastic simulator capable of predicting extreme and fatigue loads of HAWTs
- AeroDyn subroutine package (Windward Engineering) generates aerodynamic forces along turbine blades
- Turbine modeled as combination of rigid and flexible bodies
- Versatile high fidelity simulation of CART with controller included in the loop with switches for DOFs, etc.



# Simulink Model of Region 3 Controller for CART

## Adaptive collective pitch control for the CART model

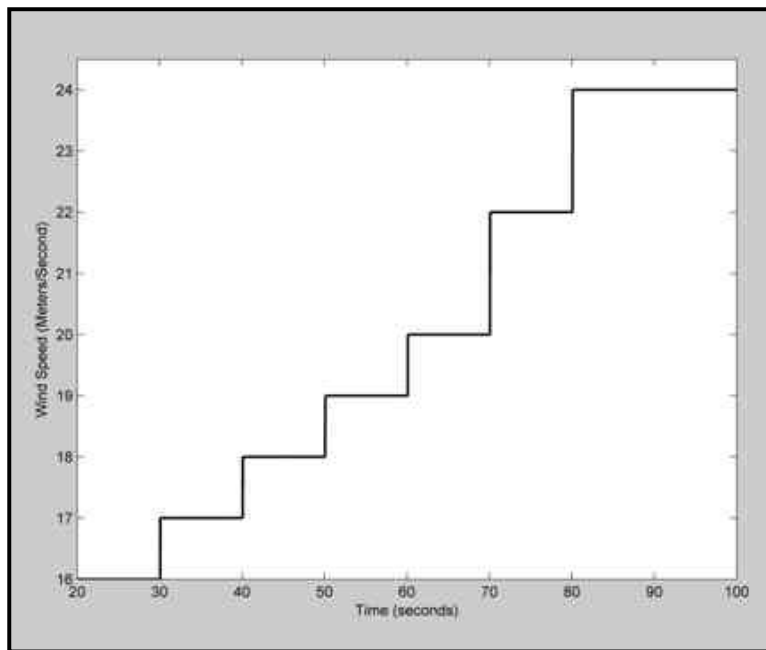




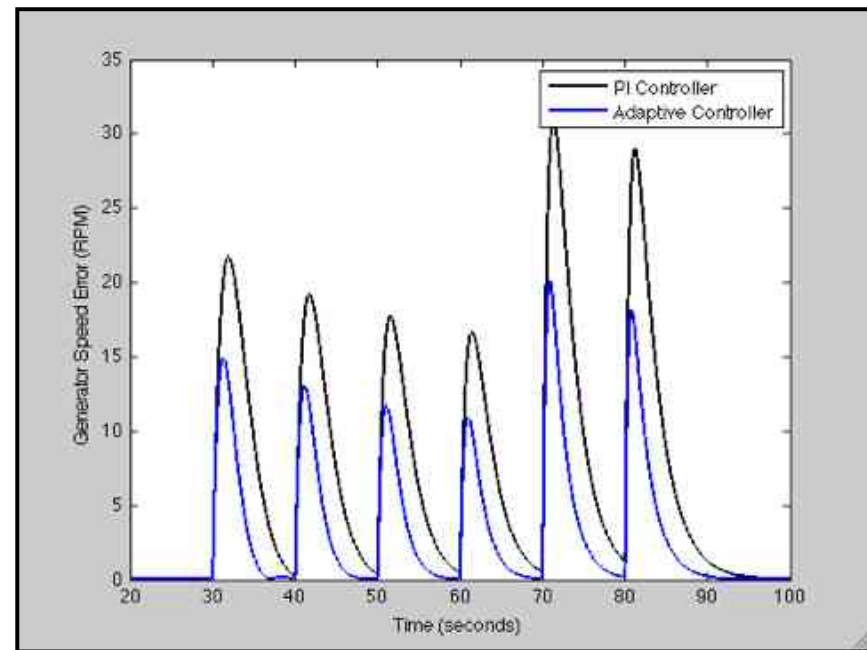
# FAST Simulation Conditions and Results

- Simulation time: 0-100 seconds
- Integration step size: 0.006 seconds
- Generator DOF switch on, all other DOF switches turned off
- Wind turbine had fixed yaw with no yaw control
- Aerodynamic forces were calculated during runs

## Step wind inflow

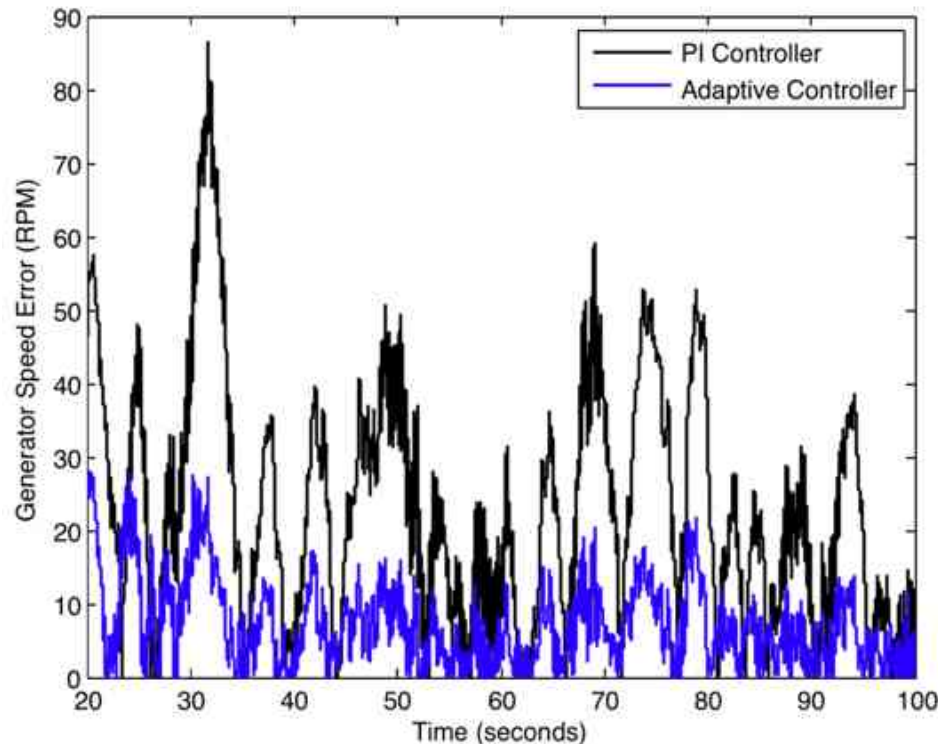


## Generator speed





# Results with Additional Flexible Modes Included



## DOF Switches Enabled

- generator
- drive train rotational flexibility
- first fore-aft tower bending-mode
- first side-to-side tower bending-mode

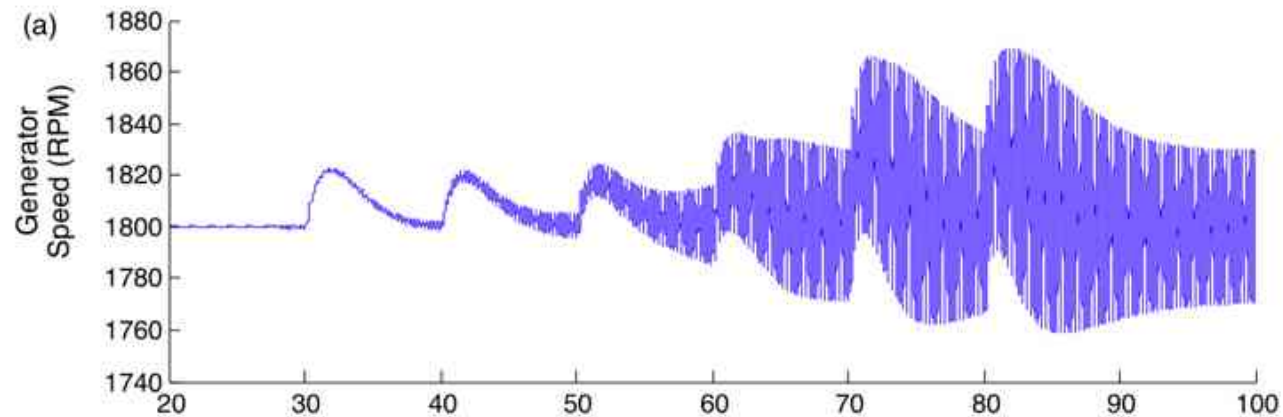
## Conclusions

- Adaptive controller was easy and quick to design
- Adaptive controller showed good generator speed regulation
- Pitch rate was comparable for both controllers with step wind
- Adaptive controller performed robustly with parameter variations

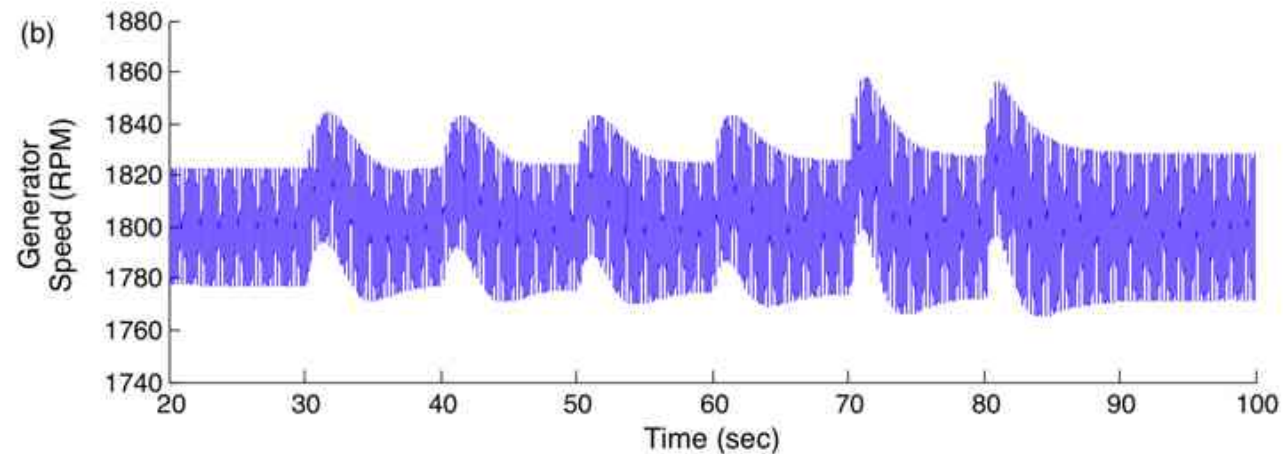


# Problems with Blade Flapwise Mode

**Baseline  
PI Controller**



**Adaptive  
Controller**

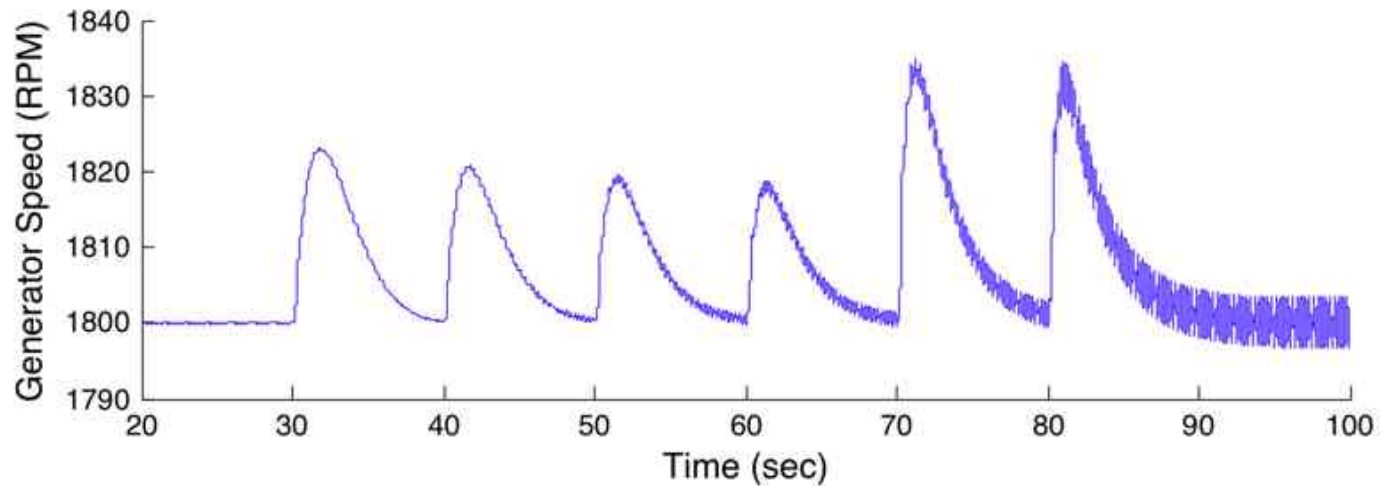


Generator speed with drivetrain torsional and first blade flapwise mode DOFs enabled and step wind inflow



# Low-Pass Filter of Generator Speed

**Baseline  
PI Controller**



Generator speed with drivetrain torsional and first flapwise blade DOFs enabled with low-pass filter on generator speed

But low-pass filters have problems ...



# Residual Mode Filter of Troublesome Modes

Assume original system:

Can be partitioned

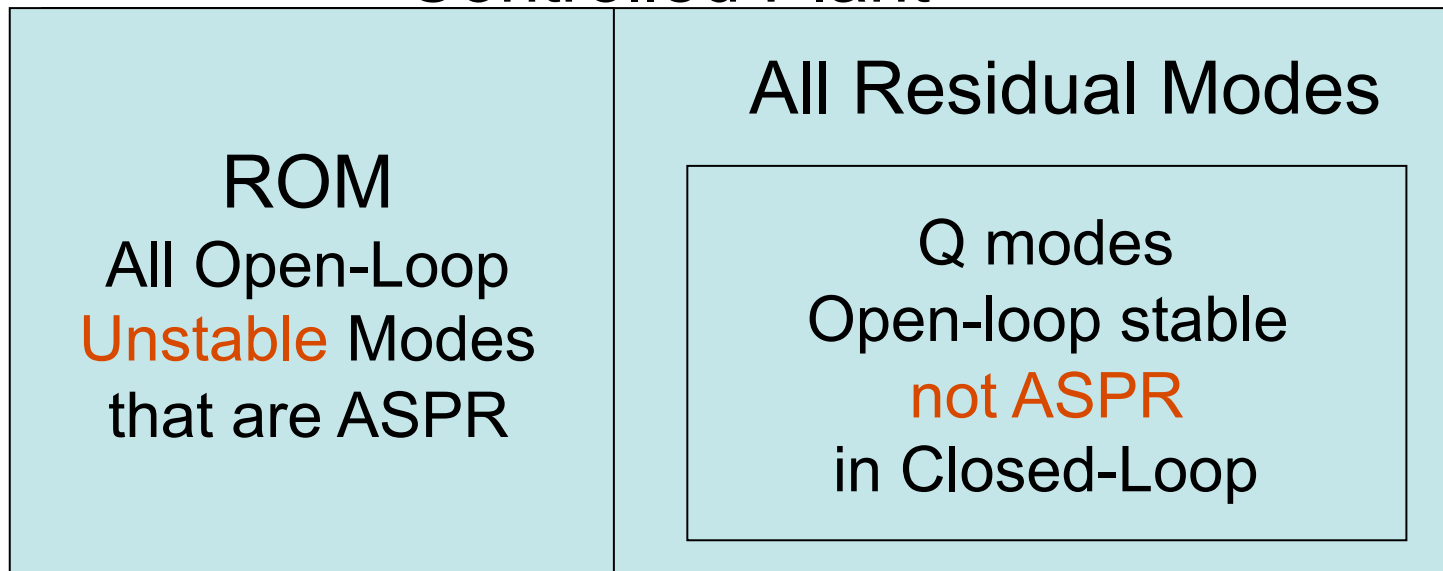
into:

$$\begin{cases} \dot{x}_p = A_p x_p + B_p u_p + \Gamma_p u_D \\ y_p = C_p x_p; x_p(0) = x_0 \end{cases}$$



$$\begin{cases} \begin{bmatrix} \dot{x} \\ \dot{x}_Q \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix} + \begin{bmatrix} B \\ B_Q \end{bmatrix} u_p + \begin{bmatrix} \Gamma \\ \varepsilon \Gamma_Q \end{bmatrix} u_D \\ y_p = \begin{bmatrix} C & C_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix}; \varepsilon \geq 0 \end{cases}$$

Controlled Plant



$(A, B, C)$  is ASPR when  $CB > 0$  and  $P(s) = C(sI - A)^{-1}B$  is minimum phase.



## Residual Mode Filter Definition and Theorem

Define the Residual Mode Filter:

$$\begin{cases} \dot{\hat{x}}_Q = A_Q \hat{x}_Q + B_Q u_p \\ \hat{y}_Q = C_Q \hat{x}_Q \end{cases}$$

and the compensated tracking error:

$$\tilde{e}_p \equiv y_p - \hat{y}_Q$$

Let  $e_Q \equiv \hat{x}_Q - x_Q$

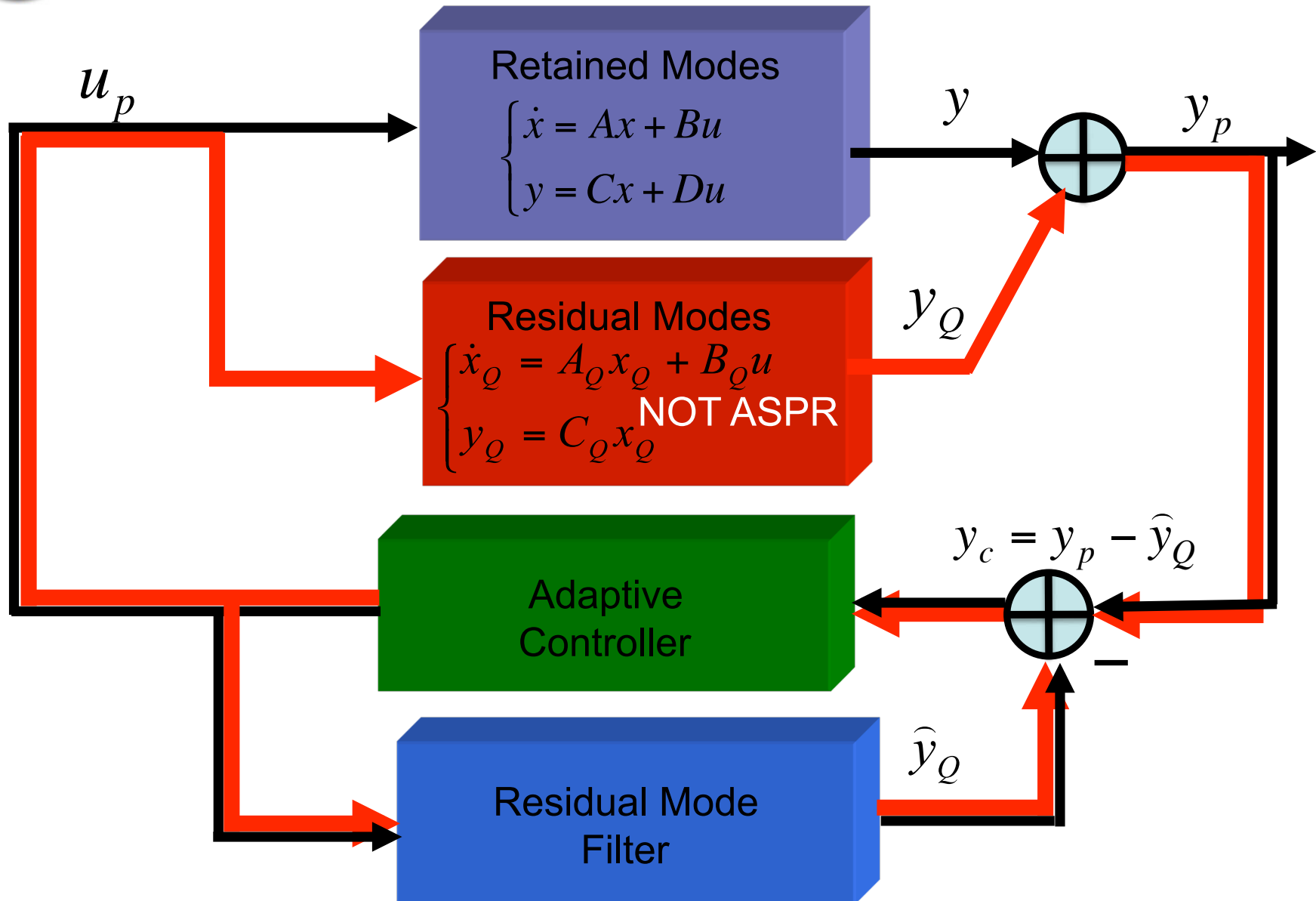
**Theorem:** Let  $(A,B,C)$  be ASPR,  $A_Q$  stable, and  $\phi_D$  bounded. Then the Modified Adaptive Controller with RMF given above produces

$$e_y = y_p \xrightarrow{t \rightarrow \infty} 0; e_Q \xrightarrow{t \rightarrow \infty} 0$$

with bounded adaptive gains  $G_e$  and  $G_D$



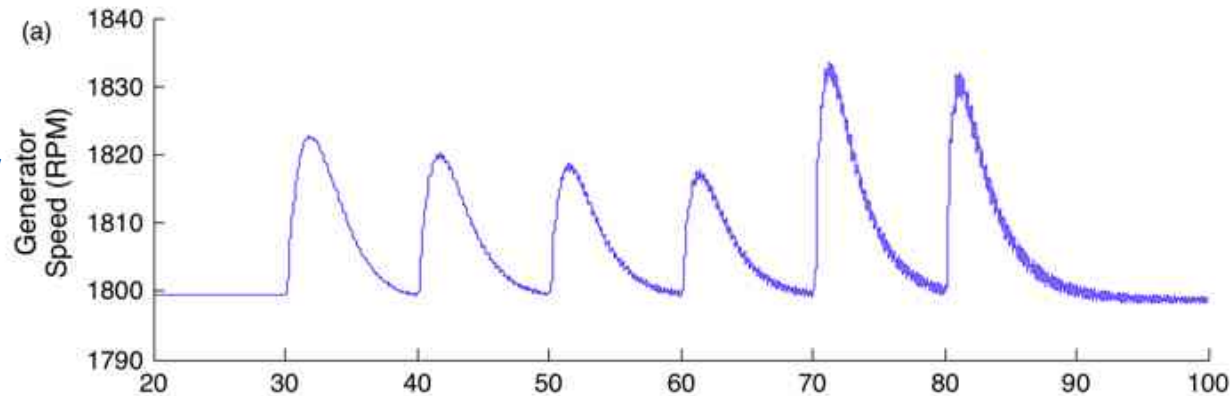
# Augmented Adaptive Controller with RMF



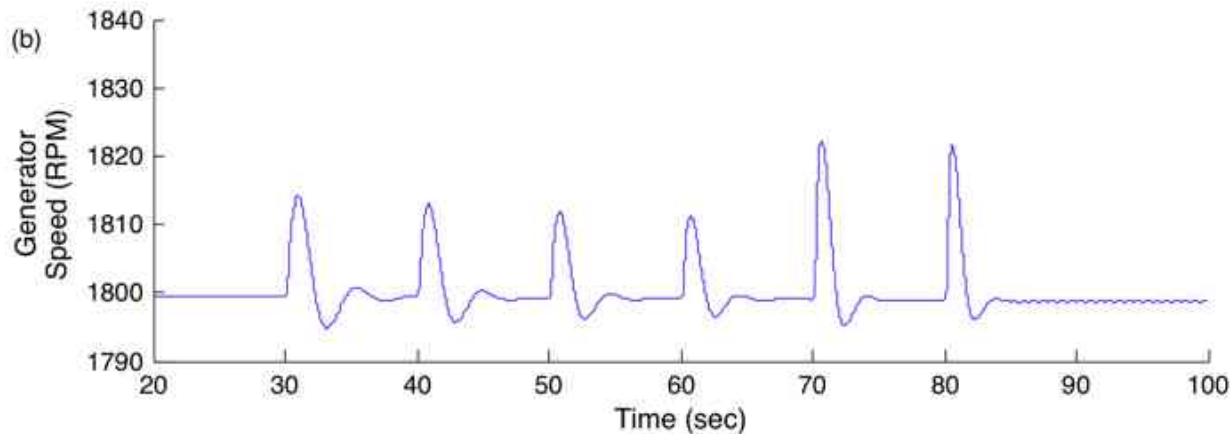


# Results with Residual Mode Filter

**Baseline  
PI Controller**



**Adaptive  
Controller**



Generator speed with drivetrain torsional and first blade flapwise mode DOFs enabled and step wind inflow. RMF was designed for drivetrain torsional mode.



## Further Work & References

- Frost, S.A., Balas, M.J., Wright, A.D., Direct adaptive control of a utility-scale wind turbine for speed regulation, *International Journal of Robust and Nonlinear Control*, 2009, 19(1): 59-71, DOI: 10.1002/rnc.1329.
- Frost, S.A., Balas, M.J., Wright, A.D., Adaptive control of a utility-scale wind turbine operating in Region 3, *Proceedings of the 28th AIAA Aerospace Sciences Meeting and Exhibit Wind Energy Symposium 2009*.
- Frost, S.A., Balas, M.J., Wright, A.D., Modified adaptive control for Region 3 operation in the presence of turbine structural modes, *Proceedings 29th AIAA Aerospace Sciences Meeting and Exhibit Wind Energy Symposium 2010*.

## Many thanks to my collaborators

**Mark Balas**

*Wyoming Wind Energy Research Center  
University of Wyoming*

**Alan Wright**

*National Renewable Energy Laboratory  
Golden, CO*